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IS THE AE INDEX A VALID INDICATOR OF SOLAR WIND POWER INPUT DURING NORTHWARD IMF?

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ABSTRACT

The fact that the auroral electrojet (AE) index is typically strongly enhanced during times of southward interplanetary magnetic field (IMF) is a major reason why a southward IMF is popularly thought to be a necessary, or at least favorable, condition for the transfer of solar wind power (and mass) across the magnetopause. Attempts to verify this by comparing variations in the IMF and the solar wind power input with subsequent concentration of energetic (keV) magnetospheric O^+ ions of terrestrial origin have failed, however (Lennartsson, 1995), casting doubt on this interpretation of the AE. As a follow-up, it is argued here, by employing simple modeling of the electrojets, that the principal difference between northward and southward IMF in the presently-produced AE can instead be accounted for by the different spatial relationships between the currents and the AE ground stations.

INTRODUCTION

The energy density of 0.1- to 16-keV O^+ ions of ionospheric origin in Earth's plasma sheet has been observed to increase with increasing solar wind energy flux (kinetic and electromagnetic alike), whether the IMF is northward or southward, and it is only some 60% larger, on average, after a few hours of southward IMF, compared to the same period of northward IMF (Lennartsson, 1995). This may appear to conflict with the strong dependence of the AE index on the IMF north-south polarity and lends new weight to an old issue (*e.g.* Mayaud, 1980, pp. 96-115, and references therein): how well, or poorly, does the AE index reflect the true strength of high-latitude currents during times of northward IMF, when the auroral ovals are contracted and the northern hemisphere electrojets may be north of all the AE ground stations?

Table 1. Averages From a Study of Oxygen Ions in the Central Plasma Sheet (Jan 1, 1978 - Mar 1, 1980)

	O^+ Energy Density (eV/cm^3)	Preceding IMF B_z (nT)	Current AE (nT)
Northward IMF	128	+ 3.7	97
Southward IMF	200	- 3.4	413

Table 1 summarizes some of the main results of Lennartsson (1995) regarding the average relationship between the energy density of O^+ ions in the central plasma sheet (inside of 23 R_E), the preceding strength (2-4 hours before) of the GSM B_z component of the IMF, and the current hourly AE. That study divided the O^+ and AE data according to the sign of B_z, requiring that B_z had remained either positive or negative for at least 3 consecutive hours (only hourly IMF values available; see Couzens and King, 1986). In contrast to the AE, the O^+ energy density is only marginally larger during southward IMF, and this small difference may be due to recent "unloading" of tail magnetic energy ("dipolarization"), rather than to enhanced influx of solar wind energy *per se*. The problem then becomes one of explaining the large difference in the average AE, especially since the ionospheric power dissipation, if AE were a true measure of current, would be expected to vary as the square of AE, rather than being just proportional to this index. The solution proposed here invokes the two B_z values in Table 1 and a well-known statistical relationship between the IMF B_z and the size and location of the northern auroral oval (Holzworth and Meng, 1975),

A SIMPLE MODEL OF AE RECORDINGS

Figure 1 assumes that the auroral "oval", specifically its equatorward edge, may be approximated by an offset circle, as discussed by Holzworth and Meng (1975), and that the electrojets may be approximated by two half-circular line currents of equal strength, situated along the equatorward edge at the somewhat arbitrary altitude of 150 km (see concluding remarks) and flowing from local noon to local midnight. These electrojets are assumed connected to outer space via two line currents following the shape of dipolar magnetic field lines, $r \propto \sin^2\theta$, between the magnetic equatorial plane and, respectively, the noon and midnight points on the oval. (These connecting currents make a negative contribution to the modeled AE, but usually by only a few tens of nT, at the most.)

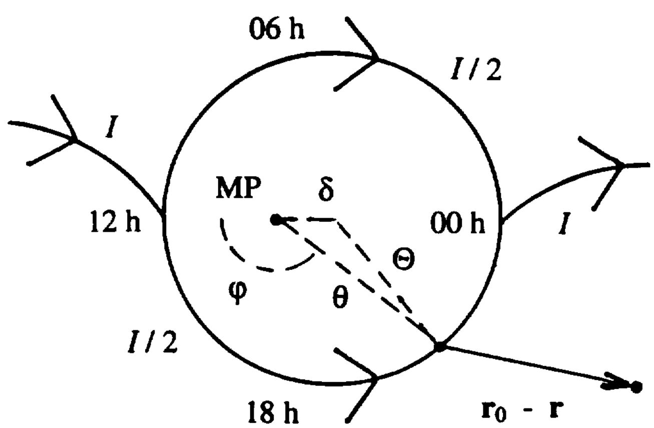

Fig. 1. Line model of high-latitude currents. Circular portion follows equatorward edge of auroral oval at 150 km altitude. Oval center is offset from magnetic pole (MP) by δ degrees. Connecting currents follow dipole field lines. Point $\mathbf{r}_0$ (magnetometer) is on Earth's surface.

Given the radius Θ of the oval, in degrees, and its offset angle δ (assumed strictly antisunward here), it is a straight-forward task to integrate, numerically, the Biot-Savart Law

$$\mathbf{B}(\mathbf{r}_0) = (\mu_0 / 4\pi) \int I(\mathbf{r})\, \mathbf{dr} \times (\mathbf{r}_0 - \mathbf{r}) / |\mathbf{r}_0 - \mathbf{r}|^3 \qquad (1)$$

along this system of line currents and obtain the magnetic field vector $\mathbf{B}$ at any point $\mathbf{r}_0$ on Earth's surface, using spherical coordinates r, θ and φ with the polar axis anti-parallel to Earth's magnetic dipole, which is assumed centered with its negative end pointing 78.6° N and 70.5° W. To provide a basis for the AE, the magnetic field only needs to be calculated at 12 points, the approximate coordinates of which are listed in Table 2, but the calculations have to be repeated many times during a complete rotation of Earth in order to simulate long-term averaging.

Table 2. Geomagnetic Latitudes and Longitudes of the 12 AE Stations (from Kamei and Maeda, 1981)

Lat (°N)	71.2	70.2	66.0	63.0	66.3	60.4	61.8	68.5	64.6	69.0	68.7	66.6
Lon (°E)	36.8	71.0	115.1	161.6	176.5	191.4	237.1	241.2	256.5	292.8	322.8	347.4

In analogy with the real process of obtaining one-minute AE values (Kamei and Maeda, 1981), only the locally horizontal and northward component H (opposite the θ unit vector here) of the disturbance field is considered, and the AE, accordingly, is calculated as the difference between the uppermost value of H recorded at any of the 12 stations in a given minute (the AU) and the lowermost value of H recorded at any of the other 11 stations in the same minute (the AL), sign included. The AE, as opposed to either the AU or the AL, has the advantage that it only depends on the total current I, at least when averaged over a 24-hour rotation of Earth (with constant I), making the relative strength of the two electrojets unimportant. Because of the 11.4° tilt of the dipole, the angular velocity of Earth, in terms of magnetic longitude, is slightly variable. Specifically, if ωt is the geographic local time angle of the North Magnetic Pole, then the corresponding angle along the magnetic equator is obtained from the arc cosine of $cos(\omega t) / \sqrt{\{1 - sin^2 11.4° \, sin^2(\omega t)\}}$. Taking this into account (a small correction) and selecting representative values of Θ and δ from Holzworth and Meng (1975), the resulting 24-hour average AE from a total current I = 510573 A is as shown in Table 3. The particular value of I has been chosen such as to produce the same average AE as listed in Table 1 for southward IMF.

Table 3. 24-Hour Average AE With Current I = 510573 A Flowing at Two Different Locations

	Circle Radius Θ	Circle Offset δ	Modeled Average AE (nT)
Northward IMF	15.5°	3.0°	96.5
Southward IMF	22.0°	5.0°	413.0

The two values of Θ are based on the two average values of IMF B_z in Table 1, using the least-squares fit in Figure 3 of Holzworth and Meng (1975), and the two values of δ have been chosen according to "quiet" (northward IMF) and "disturbed" (southward IMF) geomagnetic conditions, as suggested by parameter A_2 in Table 1 of Holzworth and Meng. Obviously, the same current produces essentially the "correct" AE for both northward and southward IMF.

The logical next step is to also make the current strength I a function of solar wind conditions. Lennartsson (1995) suggests that the ionospheric energy dissipation rate, and hence the square of the current strength, is roughly proportional to the solar wind kinetic energy flux K. As long as the AE is in the form of hourly values, it is sufficient to consider hourly values of K as well. Such one-hour averages of K can be readily obtained from the electronic OMNI file (Couzens and King, 1986),

$$K = n\, m\, |\mathbf{v}|^3 /2 + 5\, n\, k\, T\, |\mathbf{v}| /2 \qquad (2)$$

by inserting the hourly proton density n, bulk flow velocity $\mathbf{v}$ (modified to include Earth's orbital motion), and thermal energy kT listed in that file (m is the proton mass). The only remaining free parameter then becomes a constant scalar factor relating K (in W/m^2) to the square of I (in A), and the best fit to the real AE is achieved with

$$I^2 = 5.16\ 10^{14}\, K \qquad (3)$$

Since Lennartsson (1995) found the correlation of the hourly AE index with prior solar wind energy flows to be the best with a one-hour time shift, the K to be inserted in (3) is the one obtained with n, $\mathbf{v}$ and kT from the hour immediately preceding the time tag of I itself.

In order to apply this model to a large set of hourly B_z and K it is, however, necessary to impose certain restrictions on B_z. The least-squares fit for Θ in Figure 3 of Holzworth and Meng (1975),

$$\Theta = 18.9° - 0.919\, B_z \qquad (4)$$

only includes values of B_z in a range from about -5 nT to about +4 nT, and it probably does not hold much beyond that. For the purpose of comparing northward and southward IMF conditions, it is also best not to include hourly values of B_z near zero. If $|B_z|$ is thus limited to say 3-5 nT, using again the number from the hour immediately preceding the time tag of I, and if the offset angle δ, for simplicity, is set to either of two values, namely 3° for northward IMF ("quiet conditions") and 5° for southward IMF ("disturbed conditions"), then the model may be applied to all (suitable) solar wind data from the January 1, 1978, through March 1, 1980, period (same span as in Table 1, but much denser coverage). The results are listed in Table 4.

Table 4. 26-Month Average AE (nT). Includes 1409 Hours For Northward IMF, 1560 For Southward IMF

	Allowed Range of B_z	Offset δ	Modeled AE	Real AE
northward IMF	$+3$ nT $\leq B_z \leq +5$ nT	3°	89 ± 3	91 ± 3
southward IMF	-5 nT $\leq B_z \leq -3$ nT	5°	405 ± 5	404 ± 5

In this case, the modeled AE has been calculated only once each Universal Time hour, with Earth's position determined at the 30-minute mark, in order to save on computation time. The errors shown are the one sigma uncertainty in the average itself, that is the sample standard deviation divided by the square root of the number of hours.

CONCLUDING REMARKS

It may seem strange that a model as simplistic as this one can reproduce the real AE as well as it does, but there are at least two mitigating circumstances: (*i*) the point $\mathbf{r}_0$ on Earth's surface is always at a considerable distance from the current path, in this case at least 150 km, which reduces the latitudinal resolution to the order of a degree or so, and (*ii*) the longitudinal averaging implicit in Tables 3 and 4 blurs the longitudinal gradients in the current distribution.

Lowering the altitude of the "electrojets" in Figure 1 creates a larger difference in the modeled AE between northward and southward IMF. For example, if it is lowered to 100 km, and the constant in (3) is adjusted (reduced) to still produce an average AE of 405 nT for southward IMF, then the average AE for northward IMF is reduced to 82 nT. Spreading the current over several degrees in latitude would probably have the opposite effect, however, as suggested by results obtained with multiple line currents (not shown). In any case, the question posed in the title most likely has the following answer: "Yes, but only if the position of the currents is also known."

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